

Transient accretion disc-like envelope in the symbiotic binary BF Cygni during its 2006 – 2015 optical outburst

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The optical light of the symbiotic binary BF Cyg during its last eruption after 2006 shows orbital variations because of an eclipse of the outbursting compact object. The first orbital minimum is deeper than the following ones. Moreover, the Balmer profiles of this system acquired additional satellite components indicating bipolar collimated outflow at one time between the first and second orbital minima. This behaviour is interpreted in the framework of the model of collimated stellar wind from the outbursting object. It is supposed that one extended disc-like envelope covering the accretion disc of the compact object and collimating its stellar wind forms in the period between the first and second minima. The uneclipsed part of this envelope is responsible for the decrease of the depth of the orbital minimum. The calculated $UBVR_CI_C$ fluxes of this uneclipsed part are in agreement with the observed residual of the depths of the first and second orbital minima. The parameters of the envelope require that it is the main emitting region of the line $H\alpha$ but the $H\alpha$ profile is less determined from its rotation and mostly from other mechanisms. It is concluded that the envelope is a transient nebular region and its destruction determines the increase of the depth of the orbital minimum with fading of the optical light.

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1 Introduction

Symbiotic stars are interacting binaries consisting of a normal cool giant or Mira and a hot compact object accreting matter from the atmosphere of the cool companion. As a result of accretion the compact object undergoes recurrent optical outbursts. The photometric variability of the symbiotic stars is determined from both the orbital motion and the outburst events of the accretor which are often accompanied by intensive mass ejection in the form of optically thick shells, stellar wind and bipolar collimated jets. Some of these binaries are eclipsing systems whose eclipses are observed in both of their states – the quiescent and active ones.

The symbiotic system BF Cyg is an eclipsing binary consisting of a late-type cool component classified as an M5 III giant (Kenyon & Fernandez-Castro 1987; Mürset & Schmid 1999), a hot luminous compact object with a temperature of about 10^5 K and an extended surrounding nebula (Skopal 2005). Its orbital period is $757^d.2$ based on both photometric (Mikolajewska 1987) and radial velocity (Fekel et al. 2001) data.

The historical light curve of BF Cyg shows three types of activity: a very prolonged outburst, lasting for decades and similar to that of the symbiotic novae, several erup-

tions such as those observed in the classical symbiotic stars and sudden rapid brightenings lasting for a small part of the orbital period (Skopal et al. 1997). Leibowitz & Formigini (2006) suggested that some magnetic cycle in the outer layers of the giant component is connected to the origin of the outbursts. During the previous eruption in 1989 – 1993 an expanding shell with absorption lines mostly of Fe II was observed (Cassatella et al. 1992). The eclipses in this system are good seen during its previous outburst, its recent outburst begun in 2006 and the quiescent period between them (Skopal et al. 2015).

The recent 2006 – 2015 outburst of BF Cyg was first reported by Munari et al. (2006). The line spectrum was investigated by Mc Keever et al. (2011). Up to now the brightness has had four orbital minima during this outburst determined from eclipses (Skopal et al. 2015). The first of them is deeper than the following ones which means that the geometrical structure of the eclipsed outbursting compact object has changed for the time between the first and second orbital minima. Moreover, at one time between the first and second minima, since June 2009, bipolar collimated ejection appeared which lasted till April 2013. Balmer lines $H\alpha$ and $H\beta$ acquired satellite components with a velocity of about 400 km s^{-1} (Skopal et al. 2015, 2013). The blueshifted $H\beta$ component initially appeared in absorption and after September 2011 went into emission. Satellite com-

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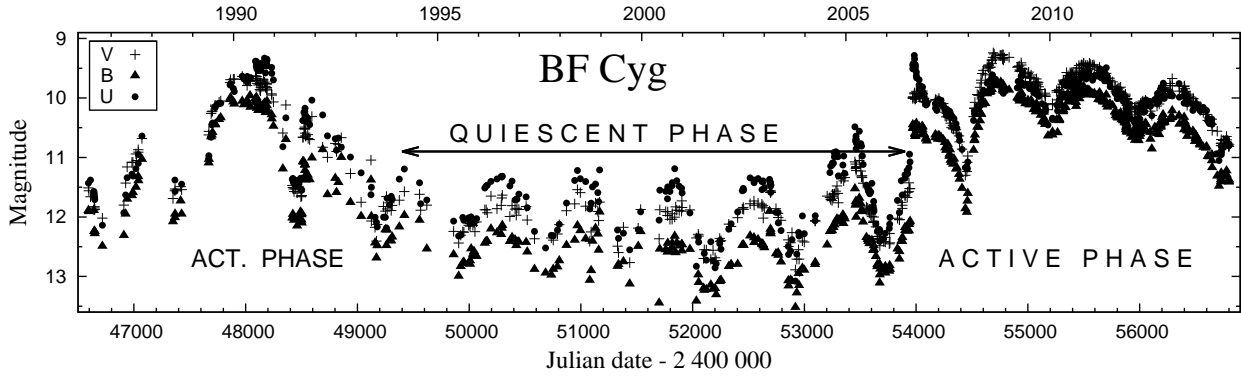


Fig. 1 The *UBV* light curves of BF Cyg during its outbursts after 1989 and 2006 and the quiescent stage between them. Adopted from Skopal et al. (2015).

ponents indicating a collimated ejection were thus observed for the first time in this system. Moreover, the $H\beta$ profile contained two additional variable P Cyg absorptions with lower velocities of -30 to -90 km s^{-1} and -250 km s^{-1} (Tomov et al. 2014). All of these data were interpreted in the framework of the model of collimated stellar wind by the outbursting object (Tomov et al. 2014).

In this work we analyse the optical light curves of BF Cyg during its 2006–2015 outburst with the aim to propose one quantitative interpretation of the decrease of the depth of the orbital minimum (eclipse) in the framework of the same model suggesting thus a possible answer to the question why did satellite components appear in the spectrum just in between the first and second orbital minima. An other task is to interpret all features of the $H\alpha$ profile in the light of this idea.

2 The behaviour of the optical light

The eclipse of the compact object in BF Cyg occurs at the time of the inferior conjunction of the giant according to the ephemeris of Fekel et al. (2001)

$$\text{JD}(\text{Min}) = 2\,451\,395^{\text{d}}.2 + 757^{\text{d}}.2 \times E.$$

The system shows periodic wave-like orbital variation in its quiescent state similar to those of AG Peg (Skopal et al. 2012). The analysis of the spectral energy distribution by Skopal (2005) shows that in quiescence the *UBV* continuum fluxes of the circumbinary nebula are comparable to the continuum fluxes of the hot compact object. Then the decrease of the brightness at the phase of the orbital minimum is determined from both an eclipse of the compact object and an occultation of a part of the circumbinary nebula. At other orbital phases the nebula is partially occulted too.

Eclipses are observed in the BF Cyg system during its outbursts as well (Skopal et al. 2012). Its last outburst began in July – August 2006 and continues up to the present time (Fig. 1) when several orbital minima were detected caused by eclipses (Skopal et al. 2015). The first minimum

is deeper than the following ones. After the first maximum the light decreases in different way compared to the next maxima. Initially the *U* light falls steeply at about one magnitude. In our view it is most probably due to decrease of the mass-loss rate of the outbursting component which moves the level of the observed photosphere back to the star and redistributes the continuum emission from longer wavelengths towards the UV region. After the initial steep fall the light begins to decrease more slowly and the basic reason for this decrease is the occultation of the circumbinary nebula. Assuming a decrease of the mass-loss rate, a part of the ejected material can remain within the gravitational potential of the compact object and begin to accrete (Tomov et al. 2014). Observational indication of the increase of the mass-loss rate can be an appearance of absorption component of the spectral lines. During the rise of the light to the second maximum the mass-loss rate was probably increased as proposed by the spectral data of Siviero et al. (2012). Strong P Cyg components of some Balmer and metal lines appeared after 2008 February 10. The light reached its second maximum at the end of 2008. Some time after that the Balmer lines acquired satellite components indicating bipolar collimated outflow (Skopal et al. 2013).

3 Interpretation

A scenario to interpret the spectrum of Z And during its 2000–2013 active phase involving two stages of the evolution of the outbursting compact object was presented in the works of Tomov et al. (2012, 2014). It is supposed that there is geometrically thin disc from wind accretion surrounding the compact object in the system in its quiescence and during the first outburst of the active phase. At the end of the first outburst some part of the ejected material accretes again and because of conservation of its initial angular momentum falls into the disc. Thus one extended disc-like envelope covering the disc forms, which locates at a greater distance from the orbital plane than the accretion disc itself. In such a way the second stage of the evolution of the outbursting

Table 1 Dereddened fluxes of BF Cyg in units of $10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$ with their inner uncertainties at the times of the orbital minima under consideration.

Date	JD–2400000	F_U	F_B	F_V	F_{R_C}	F_{I_C}
Dec. 16, 2007	54451.220	0.720 ± 0.037	0.533 ± 0.015	0.367 ± 0.011	0.330 ± 0.009	0.291 ± 0.009
Dec. 13, 2009	55179.202	1.375 ± 0.065	1.522 ± 0.044	0.883 ± 0.025	0.613 ± 0.017	0.511 ± 0.015

object begins, which is related to the following outbursts of the active phase. During the following outbursts the envelope can collimate the outflowing material and bipolar collimated outflow (collimated stellar wind) from the outbursting object can form.

According to our model the decrease of the depth of the orbital minimum implies an increase of the emission of the uneclipsed geometrical structure of the compact object. We suppose that a thin accretion disc from wind accretion has initially existed in the system BF Cyg and an extended disc-like envelope has formed after that as a result of decrease of the mass-loss rate and accretion of material from the potential well of the compact object in the period between the two orbital minima. We suppose that this envelope has collimated the stellar wind later. Some part of it is not eclipsed during the second and following minima determining their smaller depth. The jet is approximated with a spherical sector. The continuum flux determined by recombinations and free-free transitions of a spherical sector in a wind with a constant velocity v is $F_{\lambda}^{\text{cont}} \sim 1/v^2$. Then the emission of the jets is negligible because of the high velocity of the outflow.

Our aim is to calculate the $UBVR_CI_C$ emission of such a model structure and to compare it with the observed residual of the depths of the first and second minima. If the model emission (the uneclipsed part of the envelope) is close to the observed residual, we can conclude that the formation of a disc-like envelope collimating the stellar wind of the compact object is a possible reason for both the appearance of the satellite components of the spectral lines and decrease of the depth of the orbital minimum of BF Cyg. After the third minimum the system's brightness fades and the depth of the orbital minimum increases again. We suppose that former is probably due to decrease of the optical flux of the outbursting object and destruction of the envelope and the latter – to destruction of the envelope only.

4 Calculation

Gas dynamical modeling shows that a disc from wind accretion with a typical radius of $50 - 60 R_{\odot}$ and a mass of $5 \times 10^{-7} M_{\odot}$ exists in one binary system with parameters close to those of Z And in its quiescent state (Bisikalo et al. 2002; Tomov et al. 2010, 2011). During the outburst the wind of the compact object “strips” the disc and ejects some part of its mass. At the end of the outburst some part of the ejected mass locates in the potential well of the compact object. After the cessation of the wind it begins to accrete

again creating an extended disc-like envelope with a mass smaller than the mass of the initial accretion disc.

The system BF Cyg has parameters very close to those of Z And – orbital period, masses of the components and mass-loss rate of the cool giant (Fekel et al. 2001). Then we suppose that a disc from accretion of a stellar wind with a size and a mass close to that in the system Z And exists in BF Cyg in its quiescent state. During the outburst the newly appeared disc-like envelope should have smaller mass. We accept an inner radius of the envelope of $25 R_{\odot}$, equal to the radius of the pseudophotosphere of the outbursting compact object on 2008 October 23 according to Skopal et al. (2015), an outer radius of $\sim 150 R_{\odot}$ very close to the mean size of the Roche lobe of the compact object, a height of the envelope of $\sim 170 R_{\odot}$ and a mass of $\sim 3.5 \times 10^{-7} M_{\odot}$. Its mean density is thus $7.5 \times 10^{10} \text{ cm}^{-3}$. In reality the shape of this envelope differs from cylinder. With use of the orbital period and masses of the components of BF Cyg of Fekel et al. (2001) for the binary separation we obtain $492 R_{\odot}$. Fekel et al. (2001) propose a radius of the cool giant of $70 \pm 32 R_{\odot}$ at a distance to the system of 2 kpc, and Skopal (2005) $\sim 150 R_{\odot}$ at a distance of 3.8 kpc. Fekel et al. (2001) propose an orbit inclination of 75° , and Skopal et al. (1997) $70 \div 90^\circ$. We accept an inclination of 75° . In this case the radius of the giant should be large to provide eclipse and we accept a radius of $150 R_{\odot}$ according to Skopal (2005). With this radius about a half of the volume of the disc-like envelope will be visible during the eclipse at orbital phase 0.0.

To calculate the residual of the depths of the first and second orbital minima we used photoelectric and CCD data from the work of Skopal et al. (2012). The data of 2007 December 16 at the time of the first minimum are an arithmetical mean of several estimates taken in December 2007. At the time of the second minimum we used the UBV data of 2009 December 13 and R_CI_C data of 2010 January 23 since there was no infrared data in December. The stellar magnitudes were converted into continuum fluxes using the calibration from the book of Mihailov (1973). The U flux was not corrected for the energy distribution of BF Cyg in the region of the Balmer jump since we were not provided with spectral data in this region. The UBV fluxes were not corrected for the emission lines for the same reason – absence of spectral data in the UBV region. All fluxes were corrected for the interstellar reddening $E(B - V) = 0.35$ (Skopal 2005) with use of the approach of Cardelli et al. (1989) and are listed in Table 1.

We will calculate the emission of the uneclipsed part of the disc-like envelope at orbital phase 0.0 and will com-

Table 2 $UBVR_CI_C$ continuum fluxes and emission measure of the different regions in the circumbinary nebula. The fluxes are in units of $10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$ and emission measure in 10^{61} cm^{-3} .

Emitting region	F_U	F_B	F_V	F_{R_C}	F_{I_C}	$n_e^2 V$
Whole nebula	2.184	0.913	0.768	0.647	0.491	2.60 ^a
Disc-like envelope	1.856	0.776	0.653	0.550	0.417	2.21
Uneclipsed part	0.928	0.388	0.327	0.275	0.208	1.10
Residual of the depths	0.655±0.075	0.989±0.046	0.516±0.027	0.283±0.019	0.220±0.017	
r^b	42	−61	−37	−3	−5	

^a The data are for 2008 October 23 in the work of Skopal et al. (2015).

^b $r = (U - R)/R$ in per cent; U – Uneclipsed part, R – Residual of the depths.

pare it with the observed residual of the depths of the first and second orbital minima in the photometric bands $UBVR_CI_C$. Our unpublished high resolution data taken at that time do not show presence of the line He II 4686 in the spectrum of BF Cyg. Then we will assume that helium in the nebula of BF Cyg is ionized and the nebular continuum is emitted by hydrogen and neutral helium. The continuum flux determined by recombinations and free-free transitions is given by

$$F_\lambda = \frac{1 + a(\text{He})}{4\pi d^2} [\gamma_\nu(\text{H}^\circ, T_e) + a(\text{He})\gamma_\nu(\text{He}^\circ, T_e)] n_e^2 V \times \frac{c}{\lambda^2} 10^{-8}, \quad (1)$$

where $a(\text{He})$ is helium abundance relative to hydrogen, d is a distance to the system, $\gamma_\nu(\text{H}^\circ, T_e)$ and $\gamma_\nu(\text{He}^\circ, T_e)$ are continuum emission coefficients of hydrogen and helium, n_e electron density and V volume of the emitting region.

We accept an electron temperature in emitting region $T_e = 30\,000 \text{ K}$ equal to the mean temperature in the nebula according to Skopal et al. (2015). In such a case we used continuum emission coefficients at the positions of the $UBVR_CI_C$ photometric bands for this temperature from the paper of Ferland (1980) and the book of Pottasch (1984). We took the arithmetical mean of the values of the hydrogen coefficient on both sides of the Balmer limit at the position of the U band and accepted helium abundance of 0.1 (Vogel & Nussbaumer 1994). The fluxes and emission measure of the whole circumbinary nebula, our model envelope and its uneclipsed part at orbital phase 0.0 are presented in Table 2. The emission measure of the nebula was taken from Skopal et al. (2015) and its fluxes were calculated by us. The residual of the depths of the first and second orbital minima, obtained as residual of the fluxes in Table 1, is presented at the last row in Table 2. The model fluxes of the uneclipsed part are compared with this residual. It is seen that all fluxes of the uneclipsed part excepting only that in B band are close to the residual. The reason for the greater difference in the B band is rather unclear. The

quiescent emission measure of BF Cyg at phase very close to the orbital photometric maximum is $3.1 \times 10^{60} \text{ cm}^{-3}$ (Skopal 2005) and on 2008 October 23 it is $2.6 \times 10^{61} \text{ cm}^{-3}$ (Skopal et al. 2015). Its increase is thus $2.3 \times 10^{61} \text{ cm}^{-3}$. Then it appears that the emission measure of the envelope of $2.2 \times 10^{61} \text{ cm}^{-3}$ is almost equal to this increase.

5 Discussion

The evolution of the $\text{H}\alpha$ profile of BF Cyg during its outburst after 2006 was considered in the works of Skopal et al. (2013) and Skopal et al. (2015). The observational data were taken in the period July 2006 – April 2013. A part of these data is shown in the work of (Tomov et al. 2014) too. We interpreted the decrease of the depth of the orbital minimum with an appearance of a disc-like envelope whose emission measure is the greatest part of the emission measure of the whole circumbinary nebula. In such a case the Balmer lines should be emitted mainly by this envelope. The Keplerian velocity at its inner radius is 68 km s^{-1} and at the outer radius 27 km s^{-1} , using a mass of $0.6 M_\odot$ for the compact object, according to Fekel et al. (2001). Taking into consideration the orbit inclination, the radial velocities resulted from the rotation of the envelope should be $66 - 26 \text{ km s}^{-1}$. If the $\text{H}\alpha$ profile was determined only by this rotation, it should be double-peaked with a peak separation of 52 km s^{-1} and a full width at zero intensity (FWZI) of 132 km s^{-1} . The observed peaks separation of the line during the time of the collimated outflow, however, ranged from 100 km s^{-1} to 150 km s^{-1} , which means that it was broadened more than only from the rotation of the envelope. The inner uncertainty of the measurement is not more than 5 km s^{-1} . A possible additional mechanism of line broadening is a gas turbulence caused by collision of the stellar wind of the outbursting component with the envelope.

The structure of the central emission of the $\text{H}\alpha$ line, however, was double-peaked before the first orbital minimum too (Skopal et al. 2015, 2013), and the velocity of the dip between the two peaks was always of about 100 km s^{-1} .

A P Cyg absorption with a velocity of about -30 km s^{-1} was present in the $H\beta$ line from June 2009 till May 2010 (see Fig 12 in the work of Tomov et al. (2014)). The velocity of this absorption was -90 km s^{-1} in September 2011 and after that it went into an absorption dip in the emission profile with a velocity of about -30 km s^{-1} again. It was concluded that it indicates a stellar wind which exists together with the collimated ejection (Tomov et al. 2014). We suppose that this wind produces the absorption dip in the emission profile of $H\alpha$ with a velocity of about -100 km s^{-1} .

6 Conclusion

The main results of our analysis can be summarised as follows:

- We conclude that the decrease of the depth of the orbital photometric minimum of the eclipsing binary BF Cyg during its last optical outburst after 2006 and the appearance of satellite components of the Balmer lines, indicating bipolar collimated outflow at one time between the first and second orbital minima, is probably due to formation of an extended disc-like envelope covering the accretion disc of the compact object and collimating its stellar wind. An increase of the uneclipsed part of the envelope is responsible for the decrease of the depth of the orbital minimum. We assume that the envelope results from diminution of the mass-loss rate of the compact object after the first light maximum and accretion of material from its potential well in the time between the first and second orbital minima.
 - We suppose that the shape of the envelope is close to torus with an inner radius of $25 R_{\odot}$, equal to the radius of the pseudophotosphere of the outbursting object, an outer radius of $\sim 150 R_{\odot}$ very close to the mean size of its Roche lobe and a height of $\sim 170 R_{\odot}$. The mass of the envelope is accepted of $\sim 3.5 \times 10^{-7} M_{\odot}$, its mean density thus amounts to $7.5 \times 10^{10} \text{ cm}^{-3}$ and the emission measure to $2.21 \times 10^{61} \text{ cm}^{-3}$. This emission measure is almost equal to the increase of the emission measure during the outburst.
- In accordance with these parameters the central emission of the $H\alpha$ line should be produced mainly by this envelope but the analysis of its profile shows that it is additionally broadened by a gas turbulence due to collision of the stellar wind with the envelope and its double-peaked structure is determined mostly from an optically thick outflow producing an absorption dip in the emission profile.
- With use of a binary separation of $492 R_{\odot}$ and inclination of the orbit of 75° (Fekel et al. 2001) and a radius of the cool giant in the system of $150 R_{\odot}$ (Skopal 2005) about a half of the volume of the disc-like envelope will be visible during the eclipse at orbital phase 0.0. We calculated the emitted by this volume $UBVR_CI_C$ fluxes and compared them with the observed residual of the depths of the first and second orbital minima. It turned

out that the model fluxes are in agreement with the observed ones.

- We conclude that the increase of the depth of the orbital minimum with fading of the light during the outburst, on its side, is probably due to destruction of the disc-like envelope, which thus indicates its transient nature.

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